AN INVESTIGATION OF FECHNER'S COLORS.[1]

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I. STATEMENT OF PROBLEM.

If a disc composed of black and white sectors is rotated with a moderate degree of rapidity, colors appear upon the anterior and posterior edges of the sectors. In other words, when excitation by black and excitation by white precede or follow each other at certain distances, whether these distances are determined by width of sector or by rate of rotation, there does not result a gray, as one might suppose, but color. The name of *Fechner's Colors* was first applied by Brücke[2] to the colors

[1] [The author of this paper was, unfortunately, seized with illness at the conclusion of her experimental work, so that she has been unable to give the article its intended form. Chs. I-IV have received some revision; ch. V is little more than a rough draft of the discussion as originally planned. Since the author cannot return to the work in the near future, I have thought it best to publish her MS. as it stands. —E. B. T.]

[2] Brücke, Ernst: Wiener Akad. Berichte, XLIX, 1864, 21-24.

produced by rapid alternation of black and white, in honor of the discoverer of the phenomena.[1]

The colors frequently appear under conditions not standardized; *e. g.*, if we glance up suddenly, we see colored borders on the window-frame; the edges of the leaves of our book are colored while we are in the act of turning them; or the edges of the printed line are colored as our eyes move rapidly up or down the page. That is, one of the essential conditions upon which the production of the colors depends is movement; color appears when there is not perfect accommodation of the eyes.[2] But under standard conditions, when the sectors of the disc are equal and of definite size, when the rate of rotation is regulated, and when the degree of illumination is kept constant, certain colors will appear in certain places, and with variation of one or more of the conditions the colors will also vary *in a definite direction*.

Since 1838 many means have been devised for the production of the colors. The most convenient way of obtaining alternation of black and white is to use a pasteboard disc composed of sectors of different sizes. The disc can easily be rotated, and its speed can easily be regulated,—both by means of apparatus which can be kept constant through long periods. It permits of many variations in division of sectors as regards size and position. Papers of different colors or brightnesses may be put on it, or sectors of the disc may be cut out.

The difficulty, indeed, has not been to find ways of obtaining the colors, but to find the explanation for them. More than half a century has elapsed since Fechner made his experiments, and during this time scores of articles concerning intermittent stimulation of the retina have been published; but as regards the cause we may even now agree with Fechner and Brücke that we know more at the beginning than we know at the end of our investigations.[3] This result is, of course, due to our general ignorance of the exact processes which take place in the retina during and after stimulation. Experiments have been made to show that the periods of rise and fall are

[1] An article by Sir David Brewster, in the Philos. Mag., N. S. IV, 1834, describes some effects of rapid changes of retinal stimulation. This is probably the one discussion in scientific literature which might be considered a previous description of the facts noted by Fechner. But Brewster's article could with little justice be said to record the discovery of the phenomena in question, for the explanations are different, not to our point; and both discs and experiments were made with a different end in view.

[2] The instance in question is not similar to that of von Bezold's rings, dependent upon fixation. Helmholtz, Phys. Op., 2nd Ed., 156.

[3] Brücke, Ernst: Pogg. Ann., LXXXIV (whole ser. CLX), 1851, 418.

different for different colors.[1] In another way, retinal inertia is shown by means of rapid alternation of stimulation.

II. LITERATURE.

As early as 1838, there appeared an article by G. T. Fechner, *Ueber eine Scheibe zur Erzeugung subjectiver Farben*, in which he describes the disc by means of which he first produced these subjective colors.[2] The fact that Fechner discovered the phenomenon quite accidentally does not lessen its interest for us, since the description of the observations is given very fully. Fechner had prepared a disc with 18 concentric rings for the production of different shades of gray; but upon its rotation he was astonished to see a series of colors. They were not of great intensity, yet were not without a certain vivacity. He found that the colors were perceived by different persons with unequal clearness,—a fact which, in view of their subjective nature, was not considered at all surprising. The reason for the result he found in the fact that the effect made by white light does not die out with equal rapidity for all rays of which it is composed.

Much later than the appearance of the article by Fechner, Helmholtz describes the production of a "flight of colors" by means of a black and white disc.[3] When a part of the retina is exposed to rapid alternations of white light and of darkness, causing successive states of increasing and decreasing excitation, the moment of maximal excitation is not the same for all colors.

Helmholtz made use of two sorts of discs: the one consisting of a black spiral line on a white ground; the other a disc half black and half white, whose sectors were divided to form three concentric rings, the center ring divided so that its sectors formed halves, the second fourths, the outer eighths. Upon rotation, red appeared upon the anterior border of white, blue upon the posterior border. With decrease of illumination the red became orange, the blue violet. With increase, the red became rose, the blue a greenish-blue. With increase in rate of rotation, the colors passed through rose-violet to green-gray, and finally assumed an appearance similar to that of watered silk. These phenomena did not appear immediately, but only after practice, and a certain state of fatigue seemed necessary for their production. From these facts Helmholtz derived the conclusion that the moment of maximal excitation varies with the color, coming for red and violet sooner than for green.

[1] Kunkel: Arch. f. d. ges. Physiol., IX, 1874, 197.
[2] Pogg. Ann., XLV, 1838 (whole ser. CXXI), 227-232.
[3] Phys. Op., Ed. 1, 1867, 380; 2nd Ed., 1896, 530.

Aubert[1] verified the results obtained by Fechner almost as soon as they were published, and in addition noted the importance of one of the conditions necessary for the production of these colors, namely, the velocity. Extensive and accurate experiments were made to determine the exact rate which gave the most luminous colors. Aubert's general result is that too rapid or too slow rotation of the discs produces no color. These results will be discussed later in more detail.

Dove[2] does little more than report the results obtained by Fechner, although his work upon subjective colors produced by other means makes valuable additions to psychological optics.

J. Smith[3] describes the production of very brilliant luminous colors by means of rings of white or black. This is all that is of value for us; the author himself expresses the belief that the production of colors by such means overturns all accepted theories of light. He believes the experiments to be original.

Rood,[4] like Dove (pp. 171-7), obtained only lustre by alternating rather large masses of black and white. No colors are described.[5]

In 1881 a preliminary report upon the problem was made by F. J. Smith.[6] He used an ordinary wheel in making his experiments, and reports that there is an apparent relationship between spoke-interruption and wave length. Hannay experimented with a black and white disc, and came to the conclusion that response to stimulation is quickest for red; then follow green and blue[7]. He thinks that a passive observation adds to the brilliancy of the colors. This article was criticised by Napier Smith, who asked how the explanation given by Hannay accounted for the fact that black and white mixtures produce different colors, and why a certain movement should give red and the reversal blue.[8] If, however, Smith understood his discs, he would not find occasion for surprise in the fact that reversal gives a different color. To reverse the disc means to reverse the conditions. There would rather be reason for surprise if the phenomena remained constant while the conditions varied.

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[1]Aubet, H.: Physiologie der Netzhaut, 1865, § 161, 377-380. Less detail in Græfe's Hd. bh. der Augenheilkunde, II, 1876, 560. Also referred to as the Grundzüge der physiologischen Optik.

[2]Dove, H. W.: Farbenlehre, 1853, 281-283.

[3]Smith, John: Reports of Brit. Asso., XXIX, 1859, 22.

[4]Rood, O. N.: Am. Jour. Sc. (Sillman's Jour.), Ser. II, XXXV, 1865, 375.

[5][*Cf.*, however, Rood's Modern Chromatics, 1879, 93 ff.; Text-book of Color, 1881, 93 ff.]

[6]Smith, F. J.: Nature, XXIV, 1881, 140.

[7]Hannay, J. B.: Nature, XXV, Apr. 1882, 604.

[8]Smith, Napier: Nature, XXVI, May 1882, 30.

No strenuous efforts were made to solve the problem of these subjective colors for several years, until 1894, when there appeared a disc made by Benham upon a plan somewhat different from those used heretofore, which brought out the colors with astonishing clearness. The phenomena of the disc were for a few years vigorously discussed in English and American scientific literature.

The fact either that the new discs were made upon a plan widely differing from that of the old discs, or that the colors were greatly intensified by the use of fine lines rather than of large blocks of black and white, so disguised the old phenomena that they were not recognized. The greater part of the later investigations are reported as if they concerned entirely new phenomena. The 'top' appealed to many as a new problem calling for solution. The new disc, or top, is one half black, the other half white. The white half is divided into three sectors of 60° each, or four of 45° each; each angle is subtended by groups of arcs, whose radii increases arithmetically from center to circumference. This arrangement produces colors which vary from distinctly brilliant and luminous qualities to shades and tints which are disputable as regards both name and mere existence. The layman who is asked to describe a certain disc will often name the colors as accurately and unhesitatingly as the scientific observer who is more or less prejudiced by expectation.

Soon after the appearance of the disc, which has been given the name of the *artificial spectrum top*, many explanations of the phenomena were offered. One of the first attempts at explanation was made by G. D. Liveing, who exhibited the top before the Philosophical Society of Cambridge.[1] He observed that if *black* is *followed by white* at not too great rapidity a sensation of red results; if *white* is *followed by black* a sensation of blue is aroused; if black and white follow each other rapidly, drab or a neutral green is seen. These are practically the results obtained under similar conditions by all observers.

Regarding the fact there is no dispute; regarding the explanation there is scarcely any agreement. Liveing's explanation called forth almost immediately criticisms or alternative explanations from Abney,[2] Finnigan and Moore,[3] Benham,[4] and Bidwell,[5] besides notes calling attention to modifications in the preparation of the disc.

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[1]Liveing, G.D.: Cambridge Phil. Proc., Nov. 26, 1894. Also Nature, LI, Dec. 13, 1894, 167; LI, Dec. 27, 1894, 200.
[2]Abney, Capt. W. deW.: Nature, LI, Jan. 24, 1895, 292.
[3]Finnigan, J. M., and Moore, B.: Nature, LI, Jan. 24, 1895, 292-3.
[4]Benham, C. E.: Nature, LI, Dec. 27, 1894, 200.
[5]Bidwell, Shelford: Proc. Roy. Soc. London, LX, 1896, 368-379.

Only the various explanations will be taken into account here. Strangely enough, it was not until after a long discussion that Edridge-Green called attention to the fact that none of the previous writers seemed to be aware that Helmholtz had explained the phenomena in detail.[1]

Liveing explains the phenomena by saying that the impression made upon the retina by a bright light remains for some time after the cause of it is removed, and that different colors are perceived with different rapidities. Red is perceived with the greatest rapidity; the impression of blue has the longest duration; the overlapping of these sensations produces the neutral tint, a sort of gray-green. No evidence for these facts, other than the phenomena in question, is given.

Abney thinks that the phenomena would be sufficiently accounted for if the order of persistence of the three colors were violet, green, and red.

Finnigan and Moore suggest as causes irradiation (although this seems to be ruled out by the fact that change in rate of rotation causes change in color), and contrast with the surrounding white field.

Bidwell made more extensive experiments than any other of the recent investigators, but made them mainly for the purpose of showing that the solution of the problem is to be sought in the fact of sudden changes in illumination. To say this, however, is merely to point out what the problem is. In the way of explanation, Bidwell comes to the conclusion that red is without doubt due to sympathetic excitation. Blue, he says, may be due to excitation of the nerve-fibres in the neighborhood of those excited by the direct action of light; or it may be due to the scattering of light by imperfectly transparent media. He prefers to suspend judgment with regard to blue. But at any rate, he declares, the experiments show that red originates in a part of the retina not exposed to light, blue in a part where light has not ceased to act.

Rivers gives a short historical account of the phenomena.[2] He is inclined to doubt the validity of the explanations offered by Helmholtz and Fechner and to accept Bidwell's theory, although, he says, the distinctness of the red in Bidwell's experiments is to be expected if this color reaches its maximum with the rapidity ascribed to it by Kunkel.[3]

Bowditch, also, scarcely more than notes the phenomenon:[4] "when the image of a white object is moved across the retina it will appear bordered by colored fringes, since the various con-

[1] Edridge-Green, F. W.: Nature, LI, Jan. 31, 1895, 321.
[2] Rivers, W. H. R.: Schæfer's Text-book of Physiol., II, 1900, 1074.
[3] Kunkel: Arch. f. d. ges. Physiol., IX, 1874, 197.
[4] Bowditch, H. P.: Am. Text-book of Physiol., 1896, 789.

stituents of white light do not produce their maximum effects at the same time;" . . . there would then appear "colors which vary with the rate of rotation and with the amount of exhaustion of the retina."

This review of the literature shows us that there are three well-marked periods during which the phenomena of Fechner's colors have been investigated, but that scarcely any advance has been made beyond the results obtained by the original investigators of the problem, except as regards the *preparation of the discs* for the production of the colors. The reports have been cursory, and no one has attempted a systematic explanation in terms of current theories of visual sensation.

III. Apparatus and Methods.

Work was carried on in the Cornell Laboratory from the fall of 1898 until the spring of 1891. The major part of the experiments were made in a dark room, for the purpose of securing an approximately constant and easily regulable light; during only a few experiments were the discs illuminated by diffuse daylight. The greater part of the experiments were performed during the morning hours.

The power by which the discs were rotated was obtained from a Crocker-Wheeler motor, whose speed was reduced by a Pillsbury speed reducer. From this a belt ran to a Zimmermann mechanical color-mixer, which was made to rotate at the rate of 4.3 rotations in the 1 sec. The rate was tested at the beginning of each experimental hour, and often during the hour, although a variation of one or two rotations from 130 in the half-minute did not cause any appreciable change in color quality.

The observers sat close to a large black screen which stood 55.2 cm. from the disc, and in which was an opening of 21 x 15.5 cm. Behind this screen, and 43 cm. from the disc, was a Welsbach gas-burner, which furnished the whitest steady light that could be found. The black screen was protected from the heat of the lamp by a white abestos screen, which acted further as a reflector.

The following lists describe the discs in such a way that duplicates may easily be made. (For the general appearance of the discs, *cf.* Fig. 1 of the plate; for variations of the conditions, *cf.* the list of discs.) The columns lettered A, B, C, D, designate the *sector* in which a certain ring is found. The sectors are lettered *from right to left*. The figures which follow the color named stand for the *ring* which will be made when the disc is set in motion; while the color-name itself stands for the quality which lines, drawn in the position designated, will give rise to after the disc has been set in motion. For the sake of

greater convenience, in order to designate the position of the ring we shall use the name of the *color* which will appear to the normal eye while the disc is being rotated. Thus we see that, while the position of the sectors must remain constant, the position of the rings may vary within certain limits. For example,—to anticipate a little,—red and blue lines must appear in either sectors 1 or 4, but may extend through 2 or 3; green and yellow must appear in sectors 2 or 3, but cannot extend entirely through 1 or 4 without destroying their peculiar conditions. On the other hand, the groups of arcs may be at any radial distance from the center, and still fulfill the conditions necessary for the production of a certain color. Unless express statement is made to the contrary, the discs are divided into either 3 or 4 sectors, with 3 or 4 rings. Each ring is usually made up of 4 lines 1 mm. wide, the lines 3 mm. apart, the groups 5 mm. apart, the first group 10 mm. from the center. The color-names in parentheses denote the colors of the background. (The 'primary' colors are those of Bradley's colored-paper series.)

	A.	B.	C.	D.
1.	Red, 1	Green, 2	Blue, 3	
2.	Red, 1	Green, 2	Blue, 3	
3. Divided into quarters.	Red, 1	Green, 2	Blue, 3	
4. 3 broad lines.	Red, 1	Green, 2	Yellow, 3	Blue, 4
5. 5 & 6 1 mm lines.	Red, 1	Green, 2	Yellow, 3	Blue, 4
6. 3 fine lines.	Red, 1	Green, 2	Yellow, 3	Blue, 4
7. 2 broad lines.	Red, 1	Green, 2	Yellow, 3	Blue, 4
8. 3 fine lines overlapping sectors.	Red, 1	Green, 2	Yellow, 3	Blue, 4
9.	Red, 4	Green, 3	Yellow, 2	Blue, 1
10.	Red, 1	Green, 2	Yellow, 4	Blue, 3
11.	Red, 3	Green, 2	Yellow, 1	Blue, 4
12.	Red, 3	Green, 1	Yellow, 4	Blue, 2
13. Short lines.		Green, 2, 4, 5	Yellow, 1, 3	
14.	Red, 1, 3,			Blue, 2, 4
15.		Green, 1, 2, 3, 4		
16.			Yellow, 1, 3, 4 Blue, 2	Blue, 2
17.	Red, 2, 4	Red, 2, 4 Green, 1, 3		
18.	Red, 4	Red, 4	Yellow, 1, 3 Blue, 2	Blue, 2
19.			Yellow, 1, 2, 3, 4	½ sector. Green, 1, 2, 3, 4
20. Last ½ sector.	Green, 4	Green, 4	Yellow, 1, 3 Blue, 2	½ sector. Green, 1, 3 Blue, 2

21.			Green, 1, 2, 3, 4	Green, 1, 2, 3, 4	
22.	1 cm. line.	Red, 1	Green, 2	Yellow, 3	Blue, 4
23.		Red, 1			
24.		Red, 1	Green, 2		Blue, 3
25.		Red, 1, 2, 4	Red, 2, 4 Green, 3	Red, 4	
26.	Movable black sector.	Red, 1	Green, 2	Yellow, 3	Blue, 4
27.	See Plate.				
28.	$\frac{1}{16}$ black.	Red, 1	Green, 2	Yellow, 3	Blue, 4
29.	$\frac{1}{8}$ black.	Red, 1	Green, 2	Yellow, 3	Blue, 4
30.	$\frac{1}{4}$ black.	Red, 1	Green, 2	Yellow, 3	Blue, 4
31.	$\frac{3}{8}$ black.	Red, 1	Green, 2	Yellow, 3	Blue, 4
32.	$\frac{5}{8}$ black.	Red, 1	Green, 2	Yellow, 3	Blue, 4
33.	$\frac{3}{4}$ black.	Red, 1	Green, 2	Yellow, 3	Blue, 4
34.	$\frac{7}{8}$ black.	Red, 1	Green, 2	Yellow, 3	Blue, 4
35.	Plate.	Red, 1	Green, 2	Yellow, 4	Blue, 3
36.	Plate.	Red, 1	Green, 2	Yellow, 4	Blue, 3
37.	Plate.	Red, 1	Green, 2	Yellow, 4	Blue, 3
38.	Plate.	Red, 1	Green, 2	Yellow, 4	Blue, 3

Discs with colored back-grounds.

I—1.	Red, 1 (red)	Green, 2 (red)	Blue, 3 (red)	
I—2.	Red, 1 (green)	Green, 2 (green)	Blue, 3 (green)	
I—3.	Red, 1 (blue)	Green, 2 (blue)	Blue, 3 (blue)	
I—4.	Red, 1 (yellow)	Green, 2 (yellow)	Yellow, 3 (yellow)	Blue, 4 (yellow)
II—1.	Red, 1	Green, 3	Blue, 2 (red)	
II—2.	Red, 1	Green, 2	Blue, 3 (green)	
II—3.	Red, 1	Green, 2	Blue, 3 (blue)	
II—4.	Red, 1	Green, 2	Blue, 3 (yellow)	
II—5.	Blue, 4	Yellow, 3	Green, 2	Red, 1 (yellow)
III—1.	Red, 1	Green, 2 (red)	Blue, 3	
III—2.	Red, 1	Green, 3 (green)	Blue, 2	
III—3.	Red, 1	Green, 2 (green)	Yellow, 3 (green)	Blue, 4
III—4.	Red, 1	Green, 2 (Blue)	Blue, 3	
III—5.	Red, 1	Green, 2 (blue)	Yellow, 3 (blue)	Blue, 4
III—6.	Red, 3	Green, 1 (yellow)	Blue, 2	
III—7.	Red, 4	Green, 3 (yellow)	Green, 2 (yellow)	Blue, 1
IV—1.	Red, 1 (red)	Green, 3	Blue, 2 (red)	
IV—2.	Red, 1 (red)	Green, 2	Yellow, 3	Blue, 4 (red)
IV—3.	Red, 1 (green)	Green, 3	Blue, 2 (green)	
IV—4.	Red, 1 (blue)	Green, 2	Blue, 3 (blue)	
IV—5.	Red, 1 (blue)	Green, 2	Yellow, 3	Blue, 4 (blue)
IV—6.	Red, 1 (yellow)	Green, 2	Yellow, 3	Blue, 4 (yellow)
V—1.	Red, 1	Green, 2 (red)	Blue, 3 (red)	
V—2.	Red, 1	Green, 2	Yellow, 3 (red)	Blue, 4 (red)
V—3.	Red, 3	Green, 1 (green)	Blue, 2 (green)	
V—4.	Red, 1	Green, 2	Yellow, 3 (green)	Blue, 4 (green)
V—5.	Red, 1	Green, 2 (blue)	Blue, 3 (blue)	
V—6.	Red, 1	Green, 2	Yellow, 3 (blue)	Blue, 4 (blue)
V—7.	Red, 1 (yellow)	Green, 2 (yellow)	Yellow, 3	Blue, 4
VI—1.	Red, 1 (red)	Green, 2 (red)	Blue, 3 (green)	
VI—2.	Red, 1 (red)	Green, 3 (red)	Blue, 2 (blue)	
VI—3.	Red, 1 (red)	Green, 2 (red)	Yellow, 3 (yellow)	Blue, 4 (yellow)
VII—1.	Red, 1 (green)	Green, 2 (green)	Blue, 3 (red)	
VII—2.	Red, 1 (green)	Green, 2 (green)	Blue, 3 (blue)	
VII—3.	Red, 1 (green)	Green, 2 (green)	Yellow, 3 (yellow)	Blue, 4 (yellow)

VIII—1.	Red, 1 (blue)	Green, 2 (blue)	Blue, 3 (red)	
VIII—2.	Red, 1 (blue)	Green, 2 (blue)	Blue, 3 (green)	
VIII—3.	Red, 1 (blue)	Green, 2 (blue)	Yellow, 3 (yellow)	Blue, 4 (yellow)
IX—1.	Red, 1 (red)	Green, 2 (green)	Blue, 3 (red)	
IX—2.	Red, 1 (red)	Green, 2 (blue)	Blue, 3 (red)	
IX—3.	Red, 4 (red)	Green, 3 (yellow)	Yellow, 2 (yellow)	Blue, 1 (red)
X—1.	Red, 1 (green)	Yellow, 3 (red)	Blue, 2 (green)	
X—2.	Red, 1 (green)	Green, 2 (blue)	Blue, 3 (green)	
X—3.	Red, 4 (green)	Green, 3 (yellow)	Yellow, 1 (yellow)	Blue, 2 (green)
XI—1.	Red, 1 (blue)	Green, 2 (red)	Blue, 3 (blue)	
XI—2.	Red, 1 (blue)	Green, 2 (green)	Blue, 3 (Blue)	
XI—3.	Red, 3 (blue)	Green, 2 (yellow)	Yellow, 4 (yellow)	Blue, 1 (blue)
XII—1.	Red, 1 (blue)	Green, 2 (green)	Blue, 3 (red)	
XII—2.	Red, 1 (blue)	Green, 2 (red)	Blue, 3 (green)	
XII—3.	Red, 1 (red)	Green, 2 (blue)	Blue, 3 (green)	
XII—4.	Red, 1 (blue)	Green, 2 (green)	Yellow, 3 (yellow)	Blue, 4 (red)
XIII—1.		Green, 4	Yellow, 3 (yellow)	
XIII—2.	Red, 4			Blue, 3 (red)
XIII—3.	Red, 3 (blue)			Blue, 4
XIII—4.	½ white, ⅜ black, ⅛ blue		Yellow, 4	Blue, 3
XIII—5.		Green, 2	Yellow, 4	(red)
XIII—6.	Red, 2 (yellow)			Blue, 3
XIII—7.	Red, 2 (green)	Green, 4.		

Thus there were in the entire series 97 top discs,[1] and one called the Helmholtz disc,[2] all 15.5 cm. in diameter. 38 discs were simply black and white, with the arcs and lines varying as regards length and width, varying also as regards the number of lines in each group and the disposition of the groups within the different sectors. The remaining 58 discs varied from the others by having a part or all of the white semicircle replaced by one or more colors. As regards distribution of colored back-grounds, the arrangement was as follows: I 1-4 all sectors of same color; II 1-5 sector 4 (or 3 and 4 according as there were 3 or 4 sectors on disc) colored; III 1-7 middle sectors or sector colored; IV 1-6 sectors 1 and 4 of same color; V 1-7 sectors 2 and 3 of same color; VI 1-3 to XI 1-3 all sectors colored, each disc having two sectors of one color and one (or two) of another,—part with the two like sectors preceding (or following) the third, and part with the two like sectors including the third. XII 1-4 had 3 or 4 sectors of different colors. XIII 1-7 were made up of odd combinations, with a single colored sector and with only two groups of lines.

[1] Part of the discs were made by Dr. J. E. Ives, now of the Univ. of Cincinnati, who began to study the problem at the Drexel Institute, Philadelphia.

[2] The figure given by Helmholtz, Phys. Op., 2nd ed. 195, Fig. 149.

The problems which arise with this arrangement of discs, besides the phenomena of colors, are (1) the effect of length of line upon the color, (2) the effect of width of line, (3) the effect of distribution of groups, (4) the effect of background color, (5) the effect of distribution and amount of background color. The last two are, obviously, problems of contrast effect. The part played by contrast was further investigated by cutting out (by use of a gray screen) all but one group of lines. The entire series was given once to each observer, who described the colors as fully and accurately as possible; this series was checked by a second, in which the colors were matched on the "Prang Standard of Color."[1]

Although useful as a check, this second series was not, on the whole, so valuable as the first. In the first place there were not on the chart enough combinations of saturation and brightness to match all the colors on the discs; this was especially noticeable with the "rich" navy blues. Here recourse was had to the Bradley colors; but even these were unsatisfactory. Further, the luminosity of the disc color was often greater than that of the chart, the chart color seeming by comparison to be "dead" or "dull." Changes in saturation degree from one plate of the chart to another were often more rapid than changes in the disc colors, so that the colors were said to be "between plates one and two," "two and three," etc. The matched colors were often supplemented by verbal reports.

Still, in spite of these difficulties, the reports may be said to be exceptionally accurate. This accuracy is vouched for by the fact that not seldom exactly the same chart color was chosen by two or more observers, though more often the same color tone was chosen, with a varying degree of saturation.

In the second series, the direction of rotation was changed, in order to prevent any expectation, and to bring out the effect of the position of the lines. As might be expected, this had no effect upon the color-tones, but merely changed their relative positions upon the dics, their brightness and their degree of saturation. In this series red appeared in sector D, green in sector C, yellow in sector B, and blue in sector A. The observer was frequently asked to rest, always, during the change from one disc to another, and, if the need was felt, during the observation of a single disc. On the average there were about eight discs studied during each experimental hour; at first less than this number, later more, the number varying with the observer and with the condition of the observer on different days. The observers were Mrs. I. M. Bentley (By.),

[1] Prang chart, Pop. Ed., No. 1, Pub. by Louis Prang, Boston, Copyright 1898.

Miss L. Hempstead (H.), Miss M. F. McClure (M.), Dr. C. R. Squire (S.), Dr. M. F. Washburn (W.), Dr. W. C. Bagley (B.), Dr. I. M. Bentley (Be.), and Mr. R. M. Ogden (O.) (For the earlier experiments in diffuse daylight the observers were Dr. G. N. Dolson, Dr. C. R. Squire, and Mr. C. A. Perry.) Besides these, there were many who looked at only two or three discs; this was for the purpose of testing the "layman," as regards perception of the colors without expectation or fatigue.

IV. Experiments and Results.

§ 1. INTRODUCTION.

The arrangements of black and white necessary for the production of the different colors are as follows. (1) Black *followed* immediately by white gives *red*. That is, there is a sensation of red at the first stage of excitation, brighter when the excitation is continued a *relatively* long time. The resulting sensation is made more vivid if there is co-excitation by black and white (*cf.* § 4, below).

(2) Black *both followed and preceded by* white gives rise to the sensation of *green*. *a*. If black is both followed and preceded by an *equal* number of degrees of white, the resulting color is *yellowish-green*. *b*. If black is *preceded* by *less* and *followed* by *more* white, the sensation is of a more saturated, more constant *green*. *c*. If black is *preceded* by *more* and *followed* by *less* white, the sensation is of a more yellowish, less constant green, called by us *yellow*.

(3) Black *preceded* by white gives rise to the sensation of *blue*. That is, there is a sensation of blue when the excitation by white has lasted for some time and is then suddenly cut off by excitation by black. The conditions for red and blue are distinguished by the position of the lines upon which the colors appear. Black is not cessation of stimulation, but a change in the character of the stimulation.

When the lines were so arranged as to fulfill the above conditions, the following reports were made:

Table 1.

Red was chosen	156	times out of		157	99%
Green "	189	"	"	253	75%
Green or yellow "	159.5	"	"	240.5	66%
Blue "	149	"	"	164	91%

This general report necessarily leaves out of account the variations of tints and shades. These will be given with the more detailed reports.

Besides these differences, ascribed to individual peculiarities, there are also differences in color-quality caused by position (other factors remaining unchanged), by width and length of line. These problems will be discussed separately. The differences will be studied with each of the observers separately, so as to eliminate the indeterminable factor of natural individual differences; afterward, in order to determine the generality of any laws which may be found, the reports will be compared.

Before the special conditions are studied some of the more general conditions of observation may be noted.

§ 2. General Conditions. *a.* Attention.

It has been a question whether attention increases or decreases the brilliancy of the colors. This is a difficult question to answer. Perhaps it is best to answer it both affirmatively and negatively: affirmatively,—for we know that in general the effect of attention is to make the object of perception more clear and vivid; negatively,—because we know that attention fluctuates, and also because we know that the *fatigue* or *dissimilative* processes cause changes in the degree of saturation: there is light induction. We may say that attention aids in perception of color, that it clarifies the color, when not continued too long.[1] Red especially is brightened by being watched attentively. Attention seems to bring out the color when it is faint. (Be., S. and W., disc 25; B. and S., disc 27; By., discs 35-38). Closely connected with the question of attention is that of indirect vision. We saw that Hannay believes *passive* observation to be an aid in the perception of color. We can agree with him so far as to say that this is true occasionally,—but it is rather the exception than the rule. W. noted that, if she fixated beyond the disc, she could see all sorts of colors, rather mottled, covering the surface of the disc.

H. and O. noted that if they looked at the disc as a whole it had the appearance of being more generally covered with color than when they examined each separate ring. But the almost unanimous decision throughout the work was that *short periods of keen attention* aided in the perception of the colors.

b. Fatigue.

Looking "attentively" deadens the color, if the gaze is continued too long. "Too long" depends, to begin with, upon the saturation of the color. If it is merely liminal, the color will disappear almost immediately (H., disc 6, ring 3; S. 29, ring

[1]Aubert: Phys. der Netzhaut, 1865, 162, says in discussion of this point that if the ring itself be fixated it is gray, while the proximate place is blue.

4), or will change so that it cannot be matched (W. 1, ring 2; M. 9, 3 varied from III yyg 4 to B v; O. reverse of 10, 2). Very often the effect of fatigue is to make different lines of the same group appear in different colors; this was especially true of B., who scarcely ever showed general fatigue, but who showed it in this way more than the other observers. This change within the group, besides being due to fatigue, was also brought about by accidental variation of the lines. H. was especially sensitive to fatigue.

The Helmholtz disc, with its larger alternating masses of black and white, was more fatiguing than the finer alternating lines of the top disc. The disc was rotated 4.3 times in the 1 sec., at the same rate as the top discs. B., W., and O. reported on this disc, and all three reports were practically alike. Ring 1 was plainly divided into two sectors; the white was clearly tinged with yellow, and for W. had some red. Ring 2 for B. scintillated like mother of pearl, was yellowish with blue over it; for O., was blue and yellow, the yellow rather greenish,—the colors did not fuse but came in "daubs;" for W., the ring alternated yellow and violet-blue quite vividly. Ring 3 for all showed a great deal of yellow at the outer edge, as did the border of most of the other discs; for B. there was more yellow than in ring 2, and it grew yellower with gazing; there were flashes of blue-green very light and bright with dark shadows at intervals; for O., green and perhaps red were evident, but it looked as if there might be all colors 'if he could only pick them out;' for W., there were red and green, the latter a blue-green and quite bright; there was also a great deal of yellow at the edge. W. said immediately that the colors were fatigue effects, and noted this fact first in the increasing brightness of the whole disc, which disappeared after a rest. For both W. and O. all colors were gone from rings 1 and 2 after a rest; ring 3 "shimmered." For B. the colors came as rapidly as for the top discs.

c. Practice.

We must dissent from Helmholtz' assertion that practice is necessary for the perception of the colors, as well as from the statement that fatigue is necessary.[1] There were both laymen and experienced observers to whom the colors were so brilliant at first glance as to cause exclamations of surprise. But in this connection individual differences appear. To those for whom the colors were brilliant at first, they were always brilliant. To those who had difficulty in noting color at all, the colors were always dull (there were none of these among the regular ob-

[1] *Op. cit.*, 530, Fr. 502.

servers). H. probably showed the effects of practice more than any other. For her, the first three discs were black on the outer ring, with *possibly* a tinge of dark green; on the fourth disc there was a tinge of violet *at first;* discs 5 and 6 were black; disc 7 showed blue; 8 a green-blue. Afterward the green became less prominent, until it almost disappeared. Be. noted that the colors were better after looking awhile. For H. the lighter greens of rings two and three were very apt to change and hard to hold. O. saw the greens before any other colors, and his reports corresponded most clearly with the length of line. For W. the reds and blues were so brilliant that the greens by comparison could be said to have almost no color at all. The individual peculiarities continued throughout, so that they could not be said to be due to accidents of the discs.

§ 3. Rate of Rotation.

As is noted elsewhere, the effect of very rapid rotation is to produce a uniformly shaded surface. This effect was also studied by means of disc 3 which was divided into quarters. All of the colors became duller, "dirtier." Ring 3 (the outer one) was changed most. For B. it was a light green; H., black; M., black; O., black, maybe some blue; W., violet. Aubert gives an exhaustive account of the effect of rotation, working with the well-known disc with two divisions in ring one, to sixty-four in ring six.[1] When the discs are "slowing down," *i. e.*, when intermittence becomes less frequent, the colors change in brilliancy, and just before stopping, when the colors have entirely disappeared, the black lines appear very intense.

§ 4. Length of Line.

This study was made with discs on which there were shorter or longer lines than was ordinarily the case. The discs used for this study were: 8, 13, 16, 17, 18, 19, 20, 21 and 25.

Red. When the lines are lengthened the color is darkened. Colors were matched 11 times; of these 9 were taken from plates IV or V, in comparison with choice from plates II and III, sometimes IV, chosen for discs 1 and 2. Of 30 reports, including verbal descriptions and matched colors, all but one modify the report "red" by adding "there is much blue," or "black," or "red on the border only."

In disc 25, ring 1 (passing through one sector), the red is faint; ring 2 (passing through two sectors) is a deep red, redder than 1; ring 4 (passing through three sectors) is only faintly shaded with red for S. Be. can "suggest" red better than green or blue; hence might suspect the presence of red.

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[1] Aubert: *loc. cit.*

W. reported "no blue at all," showing that red was not even remotely suggested to her. These results are quite in accord with the results obtained by varying the amount of black on the disc (*cf.* § 5). It is simply another way of changing the duration of stimuli.

Green. Here again the colors are darkened, with an occasional increase in saturation. H., *e. g.*, reports II g as a match for ring 3 disc 8 (lines 1 ¼ sectors long) when reversed. This is the only color chosen from a plate with very saturated colors. 25 times the colors were chosen from plates IV to VII, and only twice from plate III. The adjectives used were often such words as "dirty," "nondescript." The changes which occur here are also in harmony with the changes brought about by changing the size of the black sector. In disc 21, where the lines were preceded and followed by equal amounts of white, the reports were VyO, IVyyg1, Vyg1, but it was added that this was just at first; the colors soon became bluish. In the reverse of disc 19, where the lines passed through the first half of the fourth and all of the third sector, the colors were reported either as blue from the first moment, or as changing sooner than in other discs. H. reported all sets of 19 as varying from VII RRv to VI v, *i. e.*, as having only a faint tinge of color. W. reported all as gray. In the reverse of disc 20, B. reported ring 1 as V BG1, and ring 3 as V BG1 to VvRv1. H. reported ring 1 as V GBG, from memory, but after this first moment as VI Bv. For W. they were all gray with some red. Ring 4 of 20, with the clock-wise turning, was reported by B. as green with some red, by H. as "a very deep green which stays," by M. as "green and quite saturated," by O. as "a distinct green." The effect of the length of line upon the green is to *darken* it, but *not to decrease* it in *saturation.*

Yellow. It may have been noted that the yellows are almost never reported as pure yellow. If it is remembered that yellow where mixed with black gives a rather greenish effect, a "dirty, nondescript" color, this fact will not be counted against our theory. The reports upon green are often modified by the adjective "yellow." No less often is the report upon yellow modified by the adjective "green;" for a yellow mixed with a black is, by this decrease in brightness, given a greenish tone. Furthermore we are little accustomed to seeing this color mixed with black. A dark blue or a dark red is recognized as being mixed with black, and such mixtures are matters of everyday perception. The same is true, too, of green; but we do not often find yellow mixed with black. We have either the pure color or light yellow, "canary," "lemon," "corn-color," etc. The reports "dirty, faded green," "nondescript," etc., are almost always referred to some modification of yellow when these

are matched. A special study of the yellows was made with the disc with a movable sector, also with discs 35-38. (The report is given below.) In disc 19, B. reports all sets as yellow, but very dark; but H., M., O., and W. report them as gray, not a dead black and white, but a gray modified by some color which they are unable to name. In disc 20, however, where there are other colors with which to contrast these same lines, ring 1 is reported by B. as olive-green, by H. as a green which soon becomes violet, by M. as dark green, by O. and W. as gray with some red. Ring 3 is reported by B. as having lines 2 and 4 a blue-green, and 3 a red-brown; H. and M. report a green which soon becomes violet; O. a black-gray; W. gray with some red. When disc 20 is reversed, ring 4 is reported by B. as V B3, by H. as VIvBv, by M. as IV Bv3, by O. as V Bv1, and by W. as being reddish.

This change into the blue tinge, which is always very faint and dull, is also in correspondence with the results obtained with the discs with the varied black sector. In order to eliminate the factor of black, and to ascertain certainly that green appeared on ring 2 and yellow on ring 3, a series of four discs was made such as is shown in the Plate, discs 35-38. At first glance By. reported ring 2 of disc 35 as green, ring 4 as a faded yellow-brown; later she said she believed it was a green-brown, but after looking again when rested said it was yellow-brown. Be. matched the second ring with IV GB6 or GBG6, adding that the disc color was a little lighter; and matched the fourth ring with IIIy6, adding that the disc was lighter than this, too. By. called ring 2 of 36 a "faint, washed out" green, ring 4 a green or yellow-brown. With indirect vision, or while looking at ring 2, By. could see green in ring 4. Be. hesitated about ring 2 for some time, wondering whether there was not some pink. He was expecting green, for the ring was next to ring 1 which was a very rich blood red. The red comes in ring 2 only occasionally, and has in it no purple. Ring 4 he called a light brown (*i. e.*, yellow in some gray), IIIyO6, and said it was darker than ring 2.

In disc 37 By. reported ring 2 as green, ring 4 as pink at first glance. Ring 4 soon grew greener and duller; but as she looked at ring 2, the color became brown again. Ring 2 matched most nearly IIIyG6, ring 4 matched IIIyO6. For Be. ring 2 was green at first (and he noted that it was greenest just as he "goes to look" directly), and after a rest matched IIIyG6 (just as By. had matched it); ring 4 was a yellow gray-brown, darker than 2, and maybe a little red. At first Be. chose IIIyO6 to match ring 4, but later changed to IIIy6, because the *yellow* was more prominent than anything else. In disc 38 the green of ring 2 was for By. much more yellow than

before and easily lost its saturation; it was matched with IIIyy6; ring 4 was much darker than ring 2, was yellow-brown with the two inside lines "quite a good green," but matched IIIyO4. Be. matched ring 2 with IIIy6 as nearest; he added that it should be greener, but yyG6 was too green. He took some time to match ring 4. It was nearest IVy4, yet he said he was *sure* there was some green in it.

These results show quite clearly that it is green which appears most plainly in sector 2, even though it is a yellow-green. The yellow undoubtedly appears when the lines are in sector 3. The fact that both Be. and By. called ring 4 of 38 *green*, and were surprised when it matched a yellow, shows that there is a natural tendency to call yellow *green* when it is mixed with black. This result is also in harmony with the Purkinje phenomenon displayed by yellow when darkened.[1]

Of course, these colors were very light in comparison with the red and blue of rings 1 and 3, on account of the very short lines. The positions of the red and blue were kept constant, so that we could be sure that any change of color was due to changes in the lines themselves.

The relative values of the green and yellow were studied with W. and S. by help of disc 26 with the movable sector. The lines were thin and farther apart than usual, and three in each group. There was no decided green or yellow for W. at all. According to the method of minimal changes, the black sector was varied from ½ to $\frac{1}{16}$ and *vice versa*. When the disc was $\frac{5}{16}$ black, W. noted that there was scarcely any red in 1, and that the blue was very much bluer; with ¼ black, there was no more red in 1 than in 2; 3 was very much lighter than any of the others and bluish; the blue was much bluer.

[1] An attempt was made to obtain, by use of the Hering mixer, some sort of an equation between the green of yellow when mixed with black, and green itself mixed with black. The experiments were made in day-light and with the Hering color papers. It was first determined that to yellow must be added 20° of black in order for the yellow to appear greenish. 16° of yellow must be added to the black before it begins to appear greenish. Black was then added to yellow and yellow to black in order to obtain the mixture which seemed to contain the greatest amount of green. This mixture was found, on several different days, to consist of 131° of yellow and 229° of black. With this mixture was equated the mixture of about 5° of white, 300° of black and 55° of green. 60° of green made the yellow appear to be reddish, a sort of orange yellow; while with 50° of green the yellow made the green appear to be blue. Hence in the former case there was too much green, and in the latter there was too much yellow. Accepting, then, the comparatively rough estimate of 55°, we may say that the color in the mixture of 131° of yellow and 229° of black might appear half green. We may say that the resulting color is a yellow-green or a green-yellow.

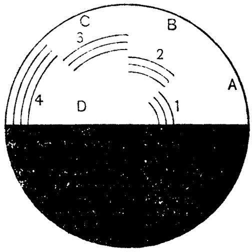
This was the same with the reverse. With S., when three was ⅛ black and the disc was being reversed, there was red-yellow on ring 3; with $\frac{3}{16}$ black, ring 3 was green-yellow. All the other rings were darker, but less distinct as regards color. This method did not prove to be so satisfactory as the one usually followed.

Blue. The effect of change of length upon the blue can be reported only in a general way, for it will be remembered that it was impossible to match the blues with any degree of accuracy. Very often the comparison was attempted, and in almost every case it was I B or BBv for saturation, but plate IV (or VI or VII) for brightness, as the case might be. We have all seen very rich dark blues, and know that mixture with black does not at all necessarily mean dullness or deadness, lack of lustre or life. It was noted, however, that when this change in brightness came there was often the remark, "now maybe I can match this." This plainly showed that a change was recognized. When disc 25 was reversed, ring 1 became a slightly green-blue, ring 2 was the usual violet-blue, ring 4 was faintly blue (perhaps by suggestion from rings 1 and 2) or black. For S., however, the ring took on the faint tinge of "chocolate" so often seen on the red lines. It is quite in the order of things that red should appear here, where we have a small section of white between black sectors and black lines,—but it is so faint as to be ordinarily overlooked, and is "suggested away" by the brilliant blues of rings 1 and 2. The change with the blue is again similar to the change with the discs carrying the small sectors of black. The blue is *dark*, but still *rich* in *saturation* and *luminous*.

§ 5. Variation of Size of Sectors.

After it was found that the length of the line caused some change in color-tone, a series of discs (26-34) was made in which the length of line was varied proportionately with the size of the sector. This proportionate variation was brought about by making discs on which the amount of black varied from 0 to ⅞. There was also a disc with the four groups of lines drawn as usual on the white, but with the black part made as a movable sector. This series of discs serves for a study of the length of lines, the effect of alternation and duration of stimuli, and also for a correlation of brightness of disc with the Purkinje phenomenon. Disc 27 is shown on the plate. On the remaining seven discs the white part is divided into four equal sectors, on which are drawn groups of arcs of the same size and radial distance as in Fig. 1 of the plate, but varying in length.

The disc which was ⅜ black varied only slightly from those



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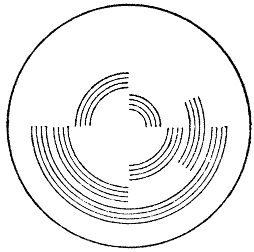
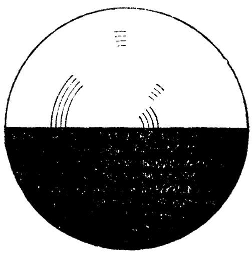


27



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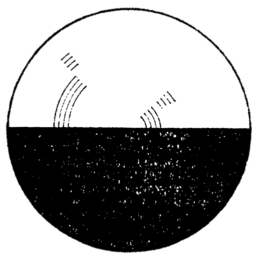

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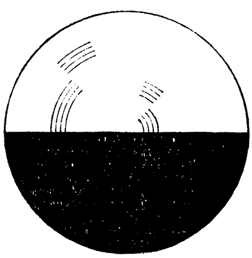

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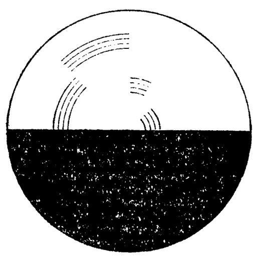

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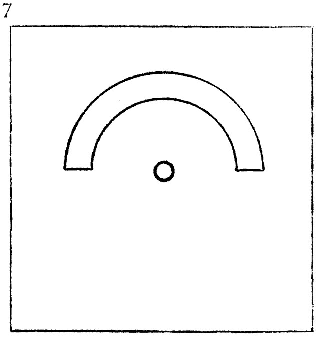

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which were ½ black. Change took place most rapidly with *increase of black.* There was a significant change in the way the reports were given. It was the darkness which first caught the attention. (The observers were all inclined to describe any striking feature before beginning to give the systematic report, and not seldom there were exclamations of pleasure or surprise.) The disc which was ⅝ black was described as looking smoked, or as if the colors were deadened by being seen through a dark veil; the black seemed to "interfere" with the brilliancy of the colors. The red was darkened for all observers by the presence of black; the lines which were usually green took on a rather pinkish shade, and were described by Be. as IIyyO5 (a very light orange), by S. as VyyO3, and by W. as a yellowish-pink, a sort of pale salmon.

The most striking change was with the disc which was ¾ black. The first unstudied impression was a dull, unsaturated red, or faded pink. And the fact that the second ring had become the brighest red and the most saturated color on the whole disc invariably caused surprise. It was reported as V Rv4, V O5, most decidedly the reddest, unsaturated but unmistakably red, a faded but uniform red. The third ring was described by three observers as green (including W., who seldom saw any tinge of green), but by one was reported as pinkish, of the same general tone as the first and second rings but more faded.

The disc which was ⅞ black became upon rotation a dull, hazy red over its entire surface. Rings 1, 2, and 3 were all of a dull red shade, 1 least saturated, 3 most. Ring 4 was at first faintly green, of a very dark shade, but it turned to red if the observer looked too long. Through this part of the series we see that the blue and yellow lines are very soon changed as regards color-quality, and that the red especially, with short duration, tends to color all the lines. The colors are thus not *dependent merely upon their position* (alternation of stimuli) *but in addition upon the actual duration of the stimulation.*

When the amount of black was decreased, the colors tended to be of a saturation equal to that of the discs ½ black, with the green perhaps lighter. Be., for example, reported ring 2 as IVg when the disc was ⅜ black, and IIg when there was ¼ black. S. also reported vivid green for the latter disc, and by matching reported IIIyG; but for the former reported only IVyyg2, and described the green as more yellowish than when there was only ¼ black. W. made no distinction between rings 2 and 3 of these discs. The red and blue were both saturated, but the green and yellow lines were reported when there was ¼ black as rather violet-gray. With clockwise turning the green was faint on ring 2, but with reverse turning both were violet-gray. With ⅜ black, rings 2 and 3 were mottled red and

very dark green; with reversal the reports for both rings were gray, with red here and there and possibly some green. At least the green for W., even though faint, was enhanced by darkness.

Ring 3 with the disc 3/8 black was different for all observers. It was hard to hold, therefore hard to match and to describe. It very evidently had an annoying, irritating effect upon the observers. They frequently asked to rest and hesitated for some time before reporting this ring as blue. Occasionally it was described as at first glance a faint yellowish-green, but this lasted scarcely more than a second. The verbal reports were blue, blue in gray, stone-blue, etc., but when the colors were matched they varied from IIIv1 with Be. to III BBv4 with S.

The disc which was only 1/8 black was accompanied by an unmistakably pleasant affective tone. The colors were reported as mixed with black, on account of the length of line, but the "spots" of color that could be separated from the black were described as *very* saturated and pretty. (It was noted that *pretty* was almost always applied to the more unmixed colors. Those that needed several adjectives to describe them, or that were hard to match, were reported more often as unpleasant, unsatisfactory colors.) The blue of ring 3 was reported as IIIvBv2 or v4, as not a very unsaturated blue or lavender.

When there was only $\frac{1}{16}$ black, the red became plum color, the green was still green although very dark, rings 3 and 4 were blue. The observers were asked not to look at the disc until it was in full motion although the change from more to less black was easily recognized. It was especially desired that they should know the construction of the disc with no black whatever, before the reports were given. The rings were reported at first as blues, or as black; but after attentive observation for a moment or two, rings 1 and 4 were reported as blue, rings 2 and 3 as green (3 perhaps as both green and violet). The green faded more quickly than the violet. There is no beginning or end to the disc. The alternation is the only feature which can differentiate greens from blues. Rings 1 and 4 may be either red or blue, but ring 4 will be darker because the lines are longer. S. was the only observer who reported a faint tinge of red in 4.

Although these subjective colors depend upon duration and alternation of stimuli, they are not all of the same saturation or brilliancy. We may permit ourselves to use the expression "mixed with black," because there are changes in saturation due to changes in the black sectors which govern the time for regeneration of the visual substances, and in the white sectors which change the duration of stimulation. The colors are mixed with black just as any subjective color is mixed with its

background. In the discs the background is either black sector or black line.

It will be noted in the above that there is a striking illustration of the Purkinje phenomenon. With *increase of black* the long-wave end of the spectrum is emphasized; there is much red, but only little green. With *increase of white* the short-wave end of the spectrum is emphasized, the long-wave end is lost. But, contrary to the phenomenon under other circumstances, the green becomes very saturated (vivid myrtle) although very dark. Our brightest light is much more moderate than the light required to make the spectrum appear blue and yellow.

§ 6. EFFECT OF WIDTH OF LINE.—Discs 2, 4, 6, 7, 9 and 22.

We may report that, as a general rule, the width has little or no effect upon the color. If the line is very thin it may seem "hard to get hold of," not enough mass to give color; but this varies with the observers, some of whom prefer the broader, others the narrower lines. Slight changes in width had no appreciable effect. W., who saw "red edges" on almost every disc, continued to see red only on the edges when the width of the lines was increased. H. and M., who almost never saw red on the edges only, saw wide lines as entirely red. B. saw red edges on the fine lines of disc 6, not on the wide lines. Disc 22 certainly had lines wide enough to give a crucial test. Here B. did see red edges, the outer edge more saturated; Be. saw a yellow halo just outside the red ring, but the ring itself was a reddish-yellowish-brown; S. saw ring 1 as plum color; O. as a brown-gray, lighter at the edges; W. saw it with red edges as usual. But for all the second ring was greenish, the most saturated on the disc, colored *all the way through*. For W. there was some green in it. Ring 3 was a blue-gray for all, for B. and O. it was lighter at the edges, for W. bluer. Ring 4 was a deep violet for all, especially marked at the inner edge. These lines are so wide that they might very well show contrast with the surrounding white field, while on the narrower lines this contrast would not exist separately from the general color-tone of the whole line. That red should appear at the edges is quite in harmony with our statement that red appears with cessation of a black sector or with beginning of excitation.

We choose at random a few cases to illustrate our statement that width has no especial effect upon color: discs, 2, 4, 6, 7.

TABLE II.

Red.	B.	H.	M.	O.
2.	IV RRv	III Rv	III Rv	IV RRO
4.	III RRv5	IIv Rv4	III Rv3	IV Rv4
6.	II Rv	III Rv	IV R1	IV RRO3
7.	III Rv1	IIIv	IVvRv	V RO1

TABLE II.—*Continued.*

Green.	B.	H.	M.	O.
2.	VgBg	IIyg	IIIyg2	IVyyg
4.	Vyg5	IIIyO3	IIIyg1	IVyg
6.	IVgyg5	IIIgyg1	IVgyg2	IVyg3
7.	IIIg3	IVg2	IVyg1	IVyyg2

§ 7. EFFECT OF POSITION UPON THE DISC.

There is at least one very striking effect due to variation of position of the rings upon the disc. The commonest arrangement is that represented by Fig. 1 of the Plate, and this is the best arrangement. We stated at the beginning of our investigation that reversal of the direction of rotation of the disc had no effect upon the general color-tone. It has, however, an invariable effect upon the shade or tint of this tone. The first ring of Fig. 1, when not reversed, gives a brilliant blood-red; but when the direction or rotation is reversed, the red becomes brownish or purple, *i. e.*, tinged with blue. The fourth ring, when not reversed, gives a brilliant, luminous and rich blue; but when reversed a duller, more violet blue. In other words, when there is reversal, the red appears in ring 4, where there is the same proportion of black and white as in ring 1, but where there is an *increase* in the *actual amount* of *white;* the blue appears in ring 1, where there is an actual *decrease* in *stimulation.*[1] This is again in accord with the results obtained with the series of discs made with greater and lesser amounts of black (*cf.* § 5). For example: B. described ring 1 of disc 1 as brilliant blood-red, but upon reversal it became IIIRRv; H. described the same ring as a brilliant lavender, luminous purplish-pink, but also chose III RRv; M. chose IV R to match this ring, while before reversal W. chose II R. Disc 5 ring 4 B. described as indigo, but matched it upon reversal with IV B. Disc 5 ring 4 O. described as black, but on reversal matched ring 1 with I BBv. Disc 6 ring 2 H. described as a "deep, rich green which very seldom changes," but upon reversal matched ring 3 with IIIgyg1, and added "it soon loses its green." The same green M. described as "quite satisfactory, best green so far," but matched it with IVgyg2. In another section we have already found that length has an influence upon color, when the discs are turned clockwise and reversed,

[1] Discs which are made of plain sectors of black and white upon rotation become a uniform gray from center to circumference, but when the sectors are notched or toothed, the conditions are changed even though the proportions of the brightnesses are still equal. Sherrington, Jour. of Phys., XXI, 1897, 47, shows that these temporal relations also effect degree of flicker, and proves that the direction of rotation changes the time of persistence of flicker.

Contrast with the colors of the neighboring ring has a slight effect upon the color. Discs 13, 15, 19, and 21, which have all lines arranged so as to produce green, were described as "monotonous, unsatisfactory, unpleasant." The effect was often very slight, because the influencing colors are themselves often only weakly saturated. It was often difficult to distinguish the cause of saturation. Take, *e. g.*, discs 11 and 12: ring 2 in disc 12, with ring 3 red, was described as light olive, vivid and rich, olive with gray; ring 4, with ring 3 red, was described as deep olive, saturated but not pure green gray. Ring 4 of 12 had the advantage of position over and above the contrast common to the two; yet ring 2 of disc 11 was described as the more saturated, or at any rate as not less saturated than ring 4 of 12. Again in disc 17 green appeared on rings 1 and 3 with red on 2 and 4; B. reported 1 as pale green, 3 deeper than 1; H. described 1 as almost pure green, while 3 was not so deep; M., too, described 1 as dark and saturated, 3 as blue-green, lighter and thinner than 1. Here some of the individual differences appeared. Ring 3 for H. and M. was more apt to become violet than was the case with B., and the advantage of having red on either side could not overcome this tendency.

§ 8. Contrast: Effect of Gray Screen.

In order to study the effect of contrast gray screens were made; one of these is shown in Fig. 2 of the Plate.

The screen was a neutral gray paper on a stiff cardboard large enough to cover the disc. A small hole in the center fitted over the screw of the spindle, so that the card could be held back close to the disc,—so close as to avoid shadow, yet not close enough to interfere with the turning of the disc. There were seven screens, each with a semi-circular opening wide enough to expose one ring of the disc: four, of course, were needed for the four-ringed discs, and three for the three-ringed. Besides cutting out the remaining rings, the gray screen also cut out the surrounding bright field of the whole disc. (The experimenter often noticed that the colors were more brilliant when the lamp-light shone in the face.)

The general effect of this screen—excluding contrast both with ring and with field—was to *decrease* the brilliancy of the color of the ring. M. studied only a few discs in this way, but the few results obtained were remarkably uniform. The reports for the reverse of discs 9 and 11 are given as illustration.

M. remarked that rings 1 and 2 of disc 11 were different when seen together, 1 being darker and greener.

The most extensive studies with the gray screen were made with B., O., and W. as observers. In all cases the rings were

TABLE III.

	DISC 9. No Screen.	DISC 9. Screen.		DISC 11. No Screen.	DISC 11. Screen.
Ring 1.	IV R	IV RRv1	1.	IIIyg1	IVyg4
" 2.	IIIgyg2	IVyyg4	2.	IIIyg3	IVyg4
" 3.	IIIyyg4	IVy4	3.	I BBv	IV BBv3
" 4.	III BBv	IV Bv2	4.	IV RRO1	III ORO2

reported on without the screen (these reports are not included in Table I), sometimes before the screen was put up, sometimes after, sometimes both.

In general the result is as noted above. O.'s results were most marked with respect to the greens. He was shown discs 5, 7, 8, 9, and 10. In all cases except disc 7 the green lines were reported "gray," without the screen "green." In disc 7 there was "a little green" with the screen, without the screen it was "greener." Rings on discs with colored sectors became "more saturated."

The most notable fact in B.'s results was that with the screen the blues were apt to be very green. In discs 1 and 10 the lines were black, in 5, 7, and 9 green-blue. The reds were least, and the greens most affected by the screen.

W. observed discs 1-25, and 30-33. The reds were least dulled or changed by the screen; the blues were less blue and bright; the greens were most changed, often losing entirely their faint green cast, and sometimes even the "red spots here and there." It was noted that toward the latter part of the investigation W. reported "no change" more often than during the first part.

More detailed investigations were made with discs 13, 15, 19 and 21. Since the rings are dulled or deadened by being all alike, it was thought that the screen might help to increase the saturation by relieving the monotony. But the effects of the two must be about equal, for the colors are the same with and without the screen. W. reported that disc 13 was greener without the screen; disc 15 showed no color difference but a brightness difference,—less bright with the screen; disc 19 showed no change, all rings were blue-gray with spots of red; disc 21 showed more red than 19; and W. noted that in ring 4 there was less *red* with the screen, if there was any change at all. Be., with disc 15, saw all lines as possibly green-gray with red here and there; the screen decreased the red. Contrast effect was manifested very slightly in the spaces, more often within the groups than between them. For O., B., and W. this influence was very slight, and (except occasionally with the blue, when the blue seemed to tint the spaces) they did not speak of it unless they were asked. For H. there was more color, but for M. there was most: she of her own accord

reported the colors of the spaces just as systematically as of the lines themselves. The yellow of the white sector was apt to give its tint to the whole disc, especially at the outer edges. The reds had faintly green (blue-green, or yellow-green) in the spaces, the greens had reddish or lavender spaces, the blues seemed almost always to give their own color to the spaces. The blue was the strongest generally, but all of the tints were very nearly liminal.

§ 9. DAY-LIGHT AND DECREASE OF LAMP-LIGHT.

The experiments made in diffuse day-light can scarcely be compared with those made in artificial light, but they may serve to show the effect of increased light. All colors except the blue were faint. The reds were reported as brown, or blue-red; the greens as gray-greens, often there was not a trace of green; yellows were never reported by this name, but either as light gray-green or (more often) as light slate blue or lavender; the blues were rich, luminous, violet-blues,—richer than simple dark blue would be. The artificial light was not decreased by exact measurement, but changes were roughly estimated. The effects were studied with disc 1. When the light is turned only a little lower than that ordinarily used, ring 1 becomes *very* dark red, 2 a pinkish-yellow, 3 a black with maybe a tinge of red. Further decrease makes ring 2 the reddest. Again decreased, ring 1 becomes dark green, 2 a blue-green which turns to pink, 3 a very black-green; decreased still further, 1 is a very rich deep green, 2 a smoked pink, 3 red at first glance turning almost immediately to green. When the light is almost out, the color of ring 1 can scarcely be distinguished from that of ring 2, but after a few seconds 2 becomes a lighter pink, 3 is darkest of all and is greenish. When the light is turned constantly and gradually, the observer watching all the time, the first change is to a yellowish effect, then to a pinkish all over the disc. At this same moment the red (ring 1) changes almost instantly to green; the green a little later becomes yellower, then red, and at the same time the blue (ring 3) becomes a red purple. With further decrease, the green of ring 1 becomes a very deep red, and 3 becomes green (but when the observer comes very close to the disc it is seen to be a black-red). The whole disc, just before the light goes out, has a very dark, faintly reddish shade.

These changes are at least roughly in accord with the Purkinje phenomenon. With day-light the lines become bluer, with decreased light they become redder or greener. These results are also in accord with those given in § 5.

§ 10. Colored Background.

After having ascertained that the color of the lines is conditioned by the alternation and duration of black and white stimuli, a series of discs was prepared on which the lines retained positions similar to those in the preceding series, but in which a portion or all of the white semicircle was replaced by a background of one or more colors. Almost from the outset there was evidence of a strong effect of simultaneous contrast. This continued so constantly and so similarly with the different observers that the Helmholtzian explanation was out of the question. Since a consciousness of the backgrounds is inessential for simultaneous contrast, we cannot hold that it is an instance of *Urtheilstäuschung*. We must hold with Hering[1] (as well as with Fechner[2]) that simultaneous contrast depends not only upon the stimulation of a certain part of the retina, but also upon the stimulation of the surrounding portions of the retina. Sherrington, at a much later date, emphasizes this same fact, and adds that this reciprocity is *subcònscious* in origin yet affects consciousness.[3] The fact that the color of the lines depends upon co-excitation is more evident here than with the black and white discs. It was also noted in § 8, that the gray screen had a greater effect upon discs with colored backgrounds than with the plain ones.

The discs upon which appear only a single background color (sets I to V inclusive, and set XIII) are more instructive for the investigation of contrast effect than the remaining sets, because they avoid complications. For the sake of convenience, we shall continue to speak of the lines as red or green or blue in order to designate their positions, although as a matter of fact these colors under certain conditions are entirely lacking. For the sake of uniformity, the colors will be studied in the order of red, green, blue and yellow, as regards both sectors and lines.

A. When red lines appeared upon a red background the quality was entirely changed. If we remember that the complement of red is a bluish-green, and if we take into account the fact that for some of our observers green is very rarely present, we may say that *when red appears upon red the lines become complementary to the surrounding background.* When the white background was entirely replaced by red, in which case the fused background became very dark red, the complementary green was also very dark, rich and well saturated. On

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[1] Hering: Lehre vom Lichtsinne, Pt. II, 1878, § 11. Also in Sitzungsb. d. kais. Akad. d. Wiss. Wien, 1872 and later.

[2] Fechner, G. T.: Pogg. Ann., *loc. cit.*

[3] Sherrington, C. S.: *op. cit.*, 38.

the other hand, if, *e. g.*, only one sector was replaced by the red, so that upon rotation the background was a light red, the lines became correspondingly light, and took on a light green-blue or blue-green that is difficult to classify. The observers were inclined to call it green-blue, but often remarked that they were not sure which color predominated. When the colors were matched they chose blues, very light, as, *e. g.*, Ib5. M. chose IIbbg2, but named it 'baby blue' even after she knew that green was present.

If, then, we leave these variations out of account, the red lines on the red background became the complement 36 times out of 39. O., in disc I 1, said the lines were slightly red, and W. reported gray once and black once. When red lines appeared upon a white sector, with red upon another, the result is practically as it is when there is no colored sector. Red was reported 28 times out of 29, green reported once (O.). When red lines appeared upon a green background, red was chosen 31 times out of 31. To be sure, the shades of red varied from a good red to a violet or dull rusty brown, but the descriptive word was always red. When red appeared upon white with blue in another sector, red was chosen 27 times, green twice, blue-green once, yellow once, and black once. The color was never pure, and there was almost invariably an unpleasant affective tone. Such adjectives as rusty, chocolate, brown, dull, unsaturated were used to modify the report 'red.' On the other hand when the red lines appeared upon white, with yellow in the background, red was reported 22 times, yellow once (B.), and this was a deeper, richer yellow than the ground. In every case the affective tone was pleasant. The colors were dainty, light yet pure, luminous, rich and brilliant.

B. When green lines appeared upon a green background, we found no such precise uniformity as with the red lines. Still, they may be said to follow the same law. When green lines appeared upon the green background, the complementary was chosen only 17 times out of 30; 9 times green was chosen, twice the lines changed almost immediately *from* green *to* red, and 3 times red and green were combined,—not fused, but appearing in different places upon the same line. Of the 9 times when green was reported, 5 concerned lines on disc 12, where the entire semicircle is green. In one other case *green* followed the lines. In 3 cases there were two sectors of green, but white followed the sector upon which the lines appeared.

From this we may draw the conclusion that the green, which we found with the black and white discs to be very weak, is not able to assert itself over and above the effect of the background color.

It should be noted that the green was very instable, that it

was very apt to become lavender, or even decidedly red. When green lines appeared upon red they remained green. These rings were often compared with the red lines on the red (which we saw became green or blue), and the green lines were found to be *less* saturated than the red. The green was the same light blue-green. For O. and W. the lines were occasionally orange or red in gray. The green lines upon blue were reported 22 times as a bronze or a yellow-green shading toward orange or pink. But it was always an unsaturated color, matched either with plates IV or V, or with rows 5 or 6 of the chart. Green upon yellow was reported 26 times as very light blue-green or green-blue, 4 times as gray with flashes of green. When green appeared upon white, with red in the background, red was reported 29 times; with green in the background, green was reported 18 times, violet only twice; with blue in the background, 8 reported green (including gobelin blue), 5 said blue, 4 red, and 1 black,—the colors were usually dark; with yellow in the background, green shading to yellow was reported 29 times, twice a combination of red and green, the colors being usually light and unsaturated.

C. When blue lines appeared upon blue, we found again a law similar to that governing red. The reports varied from reddish-brown to VI OrO, a very dull orange, and were given thus 39 times; twice there was described a royal purple surpassing any color on the chart in saturation and luminosity. Usually the colors were very hard to match on account of their low degree of saturation, and were accompanied by an unpleasant affective tone. When blue lines appeared upon a red background they became a very rich, luminous blue-green. The reports I b 1, I b 5, IIbbg 3 show that they were very light and that there was a tendency toward green-blue. When blue lines appeared upon a green background they became a dull reddish-violet (VIIrrv) tending toward a dull orange. The complement of the background color added its effect to the lines with both green and red. When blue lines appeared upon a yellow background, the color of the lines and the contrast effect reinforced each other and a rich, navy or indigo blue resulted.

When blue lines appeared upon white, with red in the background, they became a deep rich red-violet, rv, or IV r; with green in the background, they became brighter, IV bv, I bv, or IV to VII bg; with blue in the background, the color of the lines was enhanced, and became a rich wine, or purple, or violet; with yellow in the background, the blues became greenish III bbg, III bg 5 or 6, III b, usually colors of a rather high degree of saturation.

D. Yellow lines upon yellow follow tendencies similar to

those of green upon green. Blue was reported 5 times, blue-green twice, combinations of green and red twice, yellow-gray to yellow-green 14 times and gray twice. Yellow lines upon red became blue or blue green, very light and bright; upon green, a pale, dirty green when a white sector followed, but when a green followed the lines became orange or even purple; upon blue the lines were yellow, varying from a good yellow to a pink orange. When yellow lines appeared upon white, with red in the background, the lines became reddish, but more yellow if a white sector immediately followed the lines; with green in the background, the lines too became greener than usual, so that even W. saw quite clearly a tinge of faded green; with blue in the background, the lines became a deep indigo blue when blue followed immediately, but they became more reddish (rv) if white followed immediately; with yellow in the background the lines were a dull yellow, a sage green, occasionally tending to change to a reddish or bluish cast.

E. Where there are *2 colors* in the background, the lines are brightened or dulled according to the relation existing between line and color; *e. g.*, in discs VI 1-3 the red lines on red (2 red, 1 green sector) were such a dark red that there was scarcely any color for B. and H.; M. could see both red and green occasionally, which gave a gray effect; W. matched the lines with II bg. In VI 2 the red rings were still on red (2 red, 1 blue sector) but took on a very unsaturated blue-gray color for all,—only for an instant was it green for B. But in VI 3 the red ring became a dark and unsaturated green (2 red, 2 yellow sectors) for B., for H. a greenish-blue, for M. a light blue-green with occasionally the red and the yellow of the background coming over it, for W. a bright blue matching I b 1.

But when VI 1 was reversed, this threw the red over to ring 3 which was *on* green. This means that the red lines will be bright by contrast, and evidently this red is not dulled when the red sectors follow. B. reported II r, H. V r, and M. IV r with more red.

Ring 2 of this same series of discs showed also that, if the ring color was brought out by a complement, and was then followed by its own color, it was enhanced. VI 1 ring 2, green on red, with regular turning was followed by red. The report said that it was a beautiful, dainty green, apt to be bluish, a little lighter than grass-green, and W. matched it with III bg 2. But upon reversal both B. and M. chose IV gyg to match it, and H. IV yg. (This is quite dark, yellowish and unsaturated.)

Similar facts with other colors appear on other discs. XI 3 ring 4, *yellow* lines on *yellow* with *blue* following, was for B. on lines 2 and 4 blue, and on lines 1 and 3 brown, for H. green,

for M. faintly yellow green, for W. vbv. Reverse of disc VIII 3 ring 2, *yellow* lines on *blue* with *blue* following, for B. was III yyg 4, for H. IV O 4, for M. II OyO.

VIII 3 ring 2, green lines on *blue*, yellow following, was for B. green, H. green, M. y-green, W. blue and red.

XI 3 ring 2, green lines on yellow, yellow following, was for B. navy blue, H. red-violet, M. black-red, W. dark red, III v.

VI 3 ring 2, green lines on *red*, yellow following, was for B. light green with some red, H. blue-gray, M. pale green-yellow, W. an unsaturated blue.

On all of these green has not the proper circumstances to bring out its color well. Contrast the above with the reports given for X 1 ring 3, green lines on *red*, green following; for B. green, lighter than grass-green, matched I gbg1; for H. slightly green-blue, matched II gbg 1 (and sometimes gyg); for M. saturated green, matched IV g; for W. I gbg 2. These colors were reported and matched on different days. The very striking similarity between reports cannot but be noted.

Analogous descriptions could be reported at tedious length, but these are sufficient to prove the point with which this part of our discussion began. The lines are brightened or dulled according to the relations existing between the color of the lines and the colors of the background, This serves to illustrate again the fact of contrast, which appeared in the preceding discussion. It shows, as did the preceding part, how very rapidly the different excitations produce their effects. and how infallibly certain sectors (which denote certain durations of stimulation) take on their own proper colors.

Our *general conclusion* from these detailed reports will then be as follows. 1. When the lines appear upon the background of their own color-quality, they take on the color complementary to the background.

2. When the lines appear upon a white background, with a color in the background, they have practically the same color-quality that they have when the disc is plain black and white, but they are affected by a colored background according to the laws of color mixture. That is, when the color of the lines is complementary to that of the background, the color of the lines becomes duller as a result of the mixture; but when the color of the lines is related to that of the background as a neighboring spectral color, then the color of the lines becomes a mixture of the two,—brighter or duller according to the qualities of the colors mixed.

V. THEORY.

There are, without doubt, numerous other ways in which the phenomena of Fechner's Colors might be brought about, and there are many other ways in which the discs might be varied. But the important point is to discover the conditions upon which the colors are dependent; as a corollary to this followed the investigation of the conditions which served to bring out the colors in the best way possible, to produce the greatest possible saturation and purity of colors. The use of fine lines upon a white background is much better for the production of clear-cut colored areas than the use of large blocks of black and white, and better than cutting out sectors from either black or white discs. Both of these methods give larger masses of color, but the extent of colored surface can be determined with less accuracy, and variations can be made less readily. Further variations, but also greater complications, could be obtained by the use of a greater number of colored backgrounds and by the use of colored lights.

Our aim has been to avoid such complications as might lead to confusion of results, and thus obscure any law which might appear with greater simplicity of conditions. It is under very simple conditions, then, that we have obtained the preceding facts.

The phenomena of the discs cannot be disputed. Given the conditions of illumination, rate and construction of the disc as described, one can predict infallibly the general color tone which will result for the normal eye. There can even be predicted the result for the fatigued eye But this is only to state the problem, not to solve it. A theory must state the special conditions upon which the appearance of a quality in consciousness is dependent, and these conditions must necessarily be sought in specific bodily dispositions and functions. Hence we have turned to the theory of vision proposed by Ebbinghaus, because it brings us nearer to these bodily dispositions and functions than any other theory yet advanced.

The theory of fatigue must be abandoned, for the colors take on their greatest saturation at about the time required for perfect accommodation (upon the disc, not the lines), and *lose* their saturation as dissimilation continues. We cannot agree with Helmholtz that a certain amount of fatigue is necessary for the perception of the colors. The theory that the colors are due to sympathetic excitation must also be put aside. Red may be due to some extent to this cause; but there surely is no reason to think that sympathetic excitation would act in such a way with one set of lines, while the one following next to it gives the very opposite color. Hence another explana-

tion must be sought for the three remaining rings of the disc. If a satisfactory account can be given of these, there is no reason why red should not be explained in a similar way, instead of being set aside by itself as due to some peculiar disposition.

The theory that the colors are complements causing each other must be given up for the reason that it, too, cannot consistently be carried through for all colors. At first thought it may seem reasonable to explain green as being the complement of the red, but the weakness of the explanation appears when we compare the brilliancy of the green with the brilliancy of the red, and note the time of excitation which precedes the appearance of green. Even allowing that the green-yellow of the following ring may result from the same cause, we are not able to account for the brilliant, luminous blue which appears in the fourth ring. The theory of irradiation has already been given up. Contrast must also be discarded as an ultimate cause, although (as has been shown) it plays its part in the phenomena.

One naturally looks to one's facts as reinforcing or making against some existing theory of visual sensation. Unsystematic work with the discs might easily lead to the conclusion that the results would furnish verification of the Helmholtz theory; but further work would inevitablv lead one to abandon a three-color theory. In our own work it looked for some time as if there were only three colors present, even with the four-ringed discs. But the fact that the third ring (Fig. 1) changed so often to a blue-gray or stone-blue led us to believe that the excitation caused by it was of a nature different from that caused by the second ring, or concerned a different visual substance. The fact that when for any reason ring 3 grew lighter it grew yellower, led us then to believe that it was the amount of black that was obscuring the yellow: hence the series of discs was made which has already been discussed in IV § 3. When this difficulty was obviated, it was evident that the reaction to this ring was yellow. This fact was further borne out by the experiments with the colored backgrounds (IV § 9). We then turned to an examination of the four-color theories, and after a consideration of them finally selected Ebbinghaus's modification of Hering's theory as that which furnishes the most adequate, the most detailed and the most concrete explanation of the experimental results.[1]

This theory was chosen with an understanding of its uncer-

[1] Ebbinghaus, H.: Zeit. f. Psy. u. Phys. d. Sinnesorg., V, 1893, 145-238. This article gives more detail than the account in the *Grundzüge der Psychologie*, 1897, 169-263.

tainties, and of the criticisms which have been passed upon it.[1] Ebbinghaus himself accepts the Hering theory, with the reserve to which one is forced by our lack of knowledge of the physiological processes of the retina, but accepts it because it is at least typical of the processes which must be present. In the same spirit, then, in which Ebbinghaus accepts the theory of Hering, we here accept the theory of Ebbinghaus. It is a mode of representation of the facts which we have obtained. Thus we set to work with our eyes open, as it were, understanding our limitations.

According to the Ebbinghaus theory, normal color-vision is mediated by three substances that are sensitive to light. One of these, the white substance, is spread over the entire retina. It absorbs the light-rays of almost the entire visible spectrum, and this absorbed light serves to decompose it. The energy thus set free is in a form suitable for the excitation of nerves, and the result of this stimulation appears in consciousness as a sensation of brightness.

A second substance, which is found in the layer of rods and cones, and which does not extend over the entire retina, is identical with the visual-purple. It absorbs preferably the yellow rays. The decomposition-product formed by this absorption in its turn forms the visual-yellow. This visual-yellow absorbs the blue rays, forming a decomposition-product which gives rise to the visual-purple again.

A third substance, which is found in the cones and which thus covers a more limited area of the retina than either of the other substances, is called the red-green substance. Originally it is colored green and absorbs the red rays. The decomposition-product resulting from this absorption forms the red substance which absorbs green.

Thus in both chromatic substances there is a circular movement, a continual change of the one substance into the other. No substance is ever entirely exhausted. This color rhythm is always accompanied by the excitation of the white substance, by which energy is set free.

[1] Kœnig, A.: Sitzungsb. d. Akad. d. Wiss. zu Berlin, 1894, part II, 577-598, *Der menschliche Sehpurpur und seine Bedeutung für das Sehen*. Kœnig agrees with Ebbinghaus regarding the change of visual-purple into the visual-yellow which gives the sensation of blue (591). But he says that the still unknown visual substances which mediate the sensations of green and red (as well as the visual-yellow) are decomposed with more difficulty than the visual-purple (591). The results obtained from our discs disagree with this second statement.

Other important refences are: Kœnig, A.: Zeit. f. Psy. u. Phys. d. Sinnesorgane, IV, 1893-4, 241; von. Kries, J.: same Zeit., XIX, 1899, 175; von. Kries, J.: same Zeit., IX, 1895-6, 81; Hering and Hess: Pflüg. Arch. (Arch. für die ges. Phys.), LXXI, 1898, 105; Kuehne, W.: Hermann's Hd-bh. d. Phys., III, part III, chaps. 1 and 3.

Ebbinghaus differs from Hering in giving to all these changes, which are the immediate conditions of sensation, the name of dissimilation processes. He gives them all the same name because he believes that their modes of excitation are not essentially different.[1] Stimulation by one color excites all the visual-substances. Ebbinghaus objects to naming one part of the result of stimulation assimilation, and the other part dissimilation. Hence it follows that the excitation curves of complementary colors are not entirely antagonistic but partially coincide. Ebbinghaus believes that this simultaneity will explain the action of complements better than will Hering's theory that the one color blots out the other. These are the main points of divergence between the two theories.[2] Ebbinghaus attempts to bring the psychical facts into more specific relations to physiological substrates, and to give the colors a more definite temporal relation.

According to the Ebbinghaus theory, after the eye has been in a state of rest it is in a condition to have the sensation of yellow: *i. e.*, there is then a comparatively great amount of visual-purple, dissimilation of which gives rise the sensation of yellow.[3] The decomposition-product of visual-purple gives rise to the visual-yellow, by excitation of which there is produced the sensation of blue. Regeneration of the visual-yellow in turn gives a greater amount of visual-purple, which is again ready to be decomposed. Regeneration does not take place so rapidly as decomposition, and the rhythm proceeds more slowly as decomposition continues.

Ebbinghaus notes the discovery by Kuehne of the inertia of the visual-yellow,—that it often persists for hours before becoming colorless.[4] This means a heaping-up of the yellow substance, and it in turn reacts upon the visual-purple. If the visual-yellow is decomposed slowly, then the visual-purple is regenerated slowly because material is lacking. It cannot be entirely exhausted, for the visual-yellow is being spontaneously decomposed.

Kuehne experimented with the frog's retina, and found that ten minutes exposure to strong sun-light is necessary to bleach the visual-purple, and that regeneration requires from 1 to 2 hours. The rate of bleaching is much more rapid in warm-blooded animals,—sixty times more rapid than in the frog.[5]

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[1] Ebbinghaus: *op. cit.*, 185, 195–6.

[2] Christine Ladd Franklin, at an earlier date (Proc. Internal Congress Exp. Psy., London, 1892), published the same criticisms of the Hering theory. Also in Mind, N. S. II, 1893, 473; Science, XXII, 1893, 135.

[3] Ebbinghaus: *op cit.*, 202.

[4] Kuehne, W.: Hermann's Hd-bh., III, 1, 278, 287; I, 432.

[5] Also in Schaefer's Text-book of Physiol.; II, 1900, 1045.

These facts, or at least facts analogous to them, accord with the phenomena of the discs. The yellow was apt to turn blue after short periods of observation, while the blue persisted practically unchanged during long periods.

This theory of Ebbinghaus's corresponds entirely with the results obtained from our discs. Upon rotation it is ring 3 (Fig. 1) which gives rise to the sensation of yellow; *i. e.*, there is a relatively *short* white-stimulation which is suddenly cut off by black-stimulation. It is ring 4 which gives rise to the sensation of blue; *i. e.*, there is a relatively *longer* white-stimulation which is suddenly cut off by black-stimulation. This must mean, then, that the duration of stimulation is sufficient for enough of the visual-purple to be dissimilated, which dissimilation-product forms visual-yellow, excitation of which gives rise to the sensation of blue. This fact may also give us some idea of the time required for generation of visual-yellow, over and above that already present during a condition of rest, which is sufficient to give rise to the sensation of blue. This theory is further borne out by the fact that if the eye is in a state of fatigue, so that in ring 3 the eye is scarcely renewed at all by the rest, the lines which should give rise to yellow pass over into blue. H. was especially liable to such fatigue. In disc 15 (all lines in sector 3) H. saw ring 1 as violet; in disc 19 H. saw all rings as rv, and to W. they were blue-gray, while to B., M., and O. they were yg. In disc 20, where the lines were longer, B., H., M., O. and W. saw all rings as bluish. The case is similar with regard to red and green. It is ring 1 (Fig. 1) which gives us the sensation of red; *i. e.*, there is a sudden excitation which is continued. It is ring 2 which gives us the sensation of green; *i. e.*, there is white-excitation which is suddenly cut off by black excitation, there is then another white-excitation which is again suddenly cut off. If the eye is fatigued, so that the passing of the lines gives insufficient time for regeneration, the green becomes mottled with red. With W., who almost never saw green, the *gray* almost invariably has spots of red "here and there."

All the facts of the disc correspond with the Hering theory. It is the dissimilation colors, the yellow and the red which appear first, and the assimilation colors, the blue and the green, which appear second.[1]

Thus, we postulate some substance, or a series of substances, to which belongs a definite temporal reaction to white light. Even if there are no substances which correspond exactly to

[1] The temporal series red, green, blue obtained with the disc is in agreement with the series obtained by Kunkel (Pfl. Arch., IX, 1874, 197) with *adequate* stimuli reduced to equal intensities.

the theory of Ebbinghaus, the theory which he has advanced may be said to be typical of what the true theory must express when the proper physiological substrates are discovered. We may even go a step further than Ebbinghaus and make the postulate that the dissimilation of red and green takes place before the dissimilation of yellow and blue. Thus we have the complete temporal series red, green, yellow, blue.

To summarize: color sensations which have definite temporal relations to each other may be produced by the rapid alternation of black and white sectors. The colors are further dependent upon the duration of stimulation, and the co-excitation of black and white. They are also dependent in less degree upon length and width of lines; upon their position within the sector; and, as are all other subjective states, upon bodily conditions, practice, fatigue, and attention. These conditions are necessary for the production of color itself; but after it is once present its quality may be changed by change in rotation of the disc, change in amount of light, and by addition of background color. All the phenomena find a satisfactory explanation in terms of a four-component color theory.

ERRATA.

P. 496 read:

II—5.	Red, 4.	Green, 3.	Yellow, 2.	Blue, 1 (yellow)
III—7.	Red, 4.	Green, 3 (yellow)	Yellow, 2 (yellow)	Blue, 1

P. 497 read:

X—1.	Red, 1 (green)	Green, 3 (red)		Blue, 2 (green)
XIII—2.	Red, 2			Blue, 3 (red)

P. 510, line 4 read:
Purkinje phenomenon with the light-adapted eye: see Hering, Arch. f. d. ges. Physiol., lx, 1895, 519.

P. 511. First line of Table, for VgBg read Vgyg.